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Impact of Cryogenic Condition and Drill Diameter on Drilling Performance of CFRP

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Abstract: Machining of carbon fiber-reinforced polymer (CFRP) is a rather hard task due to the inhomogeneity and anisotropy of this material. Several defects occur in the material when CFRP is machined and machining quality deteriorates owing to these material properties. In recent years, liquid nitrogen has been considered an environmentally safe, clean, and non-toxic coolant used to cut various materials in order to enhance machinability and prevent damage during machining. In this study, a new, eco-friendly cryogenic machining technique called dipped cryogenic machining was applied for the drilling of CFRP. This experimental study investigated the effect of feed rate and drill diameter on the thrust force, delamination factor, surface quality and drill wear. Machined surfaces were analyzed in detail using a scanning electron microscope and atomic force microscope. Results indicated that the drilling of CFRP with the dipped cryogenic machining approach greatly improved machinability by reducing the surface roughness of the drilled parts and tool wear. However, it increased the thrust force and delamination factor.

Keywords: CFRP; cryogenic; drilling; drill wear; surface quality

1. Introduction

Carbon fiber-reinforced polymer (CFRP) has such perfect properties as high stiffness, light weight and high strength. Owing to these properties, the material is commonly used for modern aerospace industry applications [1]. Machining of composites is generally carried out to obtain desired geometrical shapes and tolerances [2]. Conventional drilling, the subject of this paper, is a widely utilized machining technique in aircraft production [3]. Khashaba et al. [4] investigated the influence of drill diameters and cutting conditions on the thrust force and drilling performance of glass fiber-reinforced epoxy (GFRE) composites. They reported that delamination-free holes in the drilling of GFRE composites were not obtained in the range of the tested parameters. El-Sonbaty et al. [5] presented the effect of the fiber-volume fraction, feed rate, cutting speed, and drill size on the thrust force, torque, and surface roughness in the drilling of fiber-reinforced composite materials. The authors concluded that cutting speed had an unimportant influence on the thrust force and surface roughness of epoxy resin, and drill diameter combined with feed significantly affected surface roughness. The influence of drill diameter, feed rate and spindle speed on delamination in the drilling process of glass fiber-reinforced polypropylene (GFR-PP) thermoplastic composites was studied by Srinivasan et al. [6]. The response surface method was used to make a model and optimize delamination damage during drilling. The result showed that the models utilized to predict delamination in the drilling of GFR-PP composites were effective. Besides this, feed rate was the most influential parameter

on delamination. Tsao and Hocheng [7] presented an estimation and evaluation of delamination when using a twist drill, candle stick drill and saw drill. In the experiments, three different drill bits with different diameters, feed rates and spindle speeds were used as cutting variables. The authors demonstrated that the feed rate and the drill diameter were the most influential factors affecting overall performance. Herbert et al. [8] made an attempt at studying the effects of cutting parameters on delamination when a bi-directional carbon-fabric-reinforced polymer composite was drilled by using uncoated and TiN-coated solid carbide drills. The authors implied that the diameter of the drill had an important effect on delamination. The experimental study also showed that delamination increased with an increase of drill diameter and feed rate and decreased with an increase of spindle speed. Palanikumar et al. [9] presented the impact of such machining parameters as feed rate, spindle speed, and drill diameter on the thrust force when drilling polypropylene laminates. They revealed that the principal factor influencing the machining process of composites was feed rate, followed by drill diameter.

There are many studies in the literature regarding the drilling of metals [10–12] such as aluminum [13], magnesium [14], steel [15], and white cast iron [16] under cryogenic conditions. However, in contrast to metals, studies in relation to the machining of polymer composites under cryogenic conditions are limited. Xia et al. [17] comprehensively investigated the influence of the cryogenic cooling process on the drilling performance of CFRP. They reported that cryogenic cooling reduced the rounding of the cutting edge of a drill bit and outer corner wear; it also improved the surface quality of drilled holes. However, this cooling process generated larger thrust force and torque, and this caused the occurrence of a larger delamination factor. Giasin et al. [18] investigated the influence of minimum-quantity lubrication and liquid nitrogen cooling in the drilling of glass–aluminum-reinforced epoxy fiber–metal laminates. They reported that the use of minimum-quantity lubrication and liquid nitrogen coolants increased the machining forces; however, they both decreased the surface roughness, adhesions and occurrence of a built-up edge on the cutting tool when compared with dry drilling. In another article by the authors [19], hole quality was evaluated by investigating the occurrence of burrs on the edges of the holes in the upper and lower aluminum sheets, and the accuracy and circularity of hole size. The results indicated that cryogenic and minimum-quantity lubrication coolants could remarkably decrease exit burr formation.

The research with regard to the drilling of polymer composites with various diameter drill bits has been summarized above. New studies on the drilling of such composites under cryogenic conditions have been carried out, especially in recent years, but these works are very limited. Furthermore, there are no other studies investigating the effects of different diameter drill bits combined with dipped cryogenic conditions on the drilling performance of polymer composites in the literature. In this paper, the drilling performance of CFRP material was experimentally investigated using a constant cutting speed and different feed rates and drill bits (4 and 6 mm diameter) under dry and cryogenic conditions.

2. Materials and Methods

The CFRP plate used in the experiments was fabricated from plain, woven, carbon-fiber fabric that is of 0/90° fiber orientation. Epoxy resin was used as the matrix. The plate was 5 mm thick with the dimensions 500 mm × 500 mm. The drilling experiments were conducted on a three-axis vertical machining center under dry and cryogenic cutting conditions. The drill bits were solid carbide drills with a diameter of 4 and 6 mm. These drills were chosen due to their special application for the machining of fiber-reinforced materials (Figure 1). A new drill bit was used for machining each hole to avoid any tool wear effect.

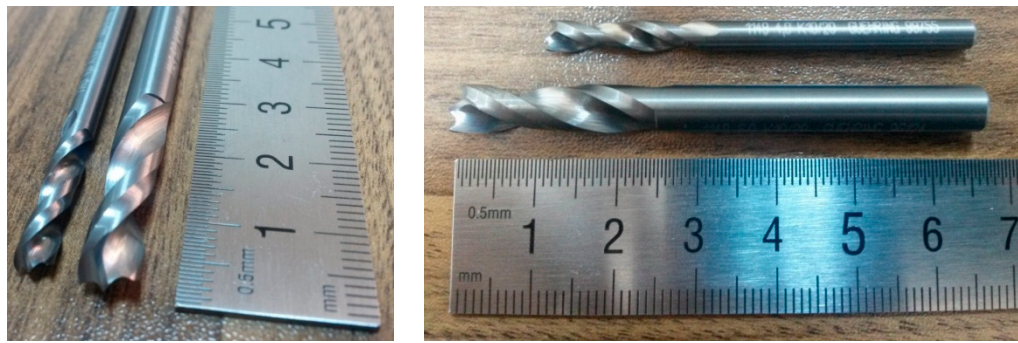


Figure 1. Drill bits used in the experiments.

The machining control factors considered for the experiment were feed rate and drill diameter. The cutting speed considered for the experiments was at a constant level of 50 m/min, the feed rates were at four levels—0.075, 0.15, 0.225, and 0.3 mm/rev—and the drill diameters were at two levels, 4 and 6 mm. The cutting parameters and their levels were chosen by taking into account the authors' experiments, previous studies published by other authors, and the recommendations of the cutting tool catalog. Generally, a drill that has the same diameter as the thickness of the plate to be drilled is used. In this study, in order to investigate the effects of drill diameter on the drilling of CFRP, both smaller (4 mm) and larger (6 mm) diameter drills than the thickness of the plate (5 mm) were utilized. A total of 16 experimental runs were conducted; eight were carried out in dry conditions and eight in cryogenic conditions. A photographic view of the experimental set-up is presented in Figure 2. The experimental set-up consisted of a drilling machine, an adjustable fixture, and a piezoelectric dynamometer. The dynamometer was rigidly mounted on the machine table. The CFRP composite was held by an adjustable fixture clamped to the piezoelectric dynamometer. In this study, liquid nitrogen (LN_2) at -196°C was used as the cryogenic coolant. The CFRP was machined in a thermally insulated fixture that was full of liquid nitrogen. The purpose of using the thermally insulated fixture was to hinder the hazardous effects of LN_2 on the dynamometer and the machining center.

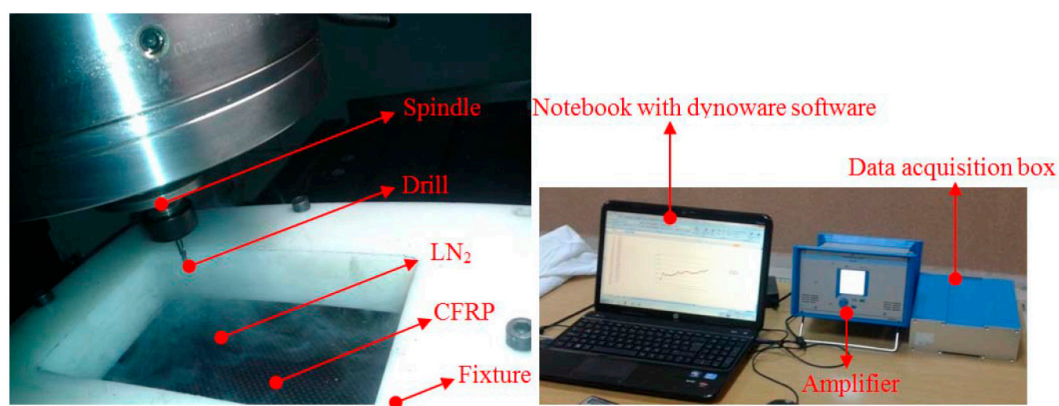


Figure 2. Experimental set-up.

During the drilling operation, the thrust force was measured and monitored with the help of a Kistler 9257B type dynamometer (Kistler, Winterthur, Switzerland), a data acquisition box, and an amplifier. The signal was transmitted through the amplifier to a PC for data collection. The exit-hole surface delamination was recorded using an Olympus SZX7 stereo trinocular microscope with $12.5\times$ magnification. In addition, scanning electron microscope (SEM) (Quanta SEM, FEI Company, Hillsboro, OR, USA) analyses were also utilized to facilitate the delamination of the hole damage and tool wear induced by the drilling. The average surface roughness (R_a), root mean

square roughness (R_q) and the three-dimensional (3D) view of the drilled hole were measured offline using an atomic force microscope (AFM) (NanoMagnetics Instruments, Oxford, UK).

3. Results and Discussion

Drilling experiments were performed under dry and dipped cryogenic conditions using solid carbide drills with the size of 4 and 6 mm and varying feed rates. The machinability of CFRP was evaluated by the thrust force, delamination factor, hole surface quality of the CFRP and tool wear.

3.1. Evaluation of Thrust Force and Delamination Factor

During a drilling operation, the determination of the thrust force is important in order to define (determine) the delamination of the CFRP material. Figure 3a illustrates a sample chart of overall thrust force–time cycles for CFRP drilling. The feed rate and cutting speed were held constant at 0.075 mm/rev and 50 m/min. Figure 3b shows a sample chart of the overall thrust force for the four feed rates examined (0.075, 0.15, 0.225 and 0.3 mm/rev.) at 50 m/min cutting speed. At the beginning of the cycles when the center and chisel edges of the cutting tool come into contact with the workpiece, the thrust force rises quickly. This is due to the high thrust force at the chisel edge region of the drill. The thrust force remains stable for a short time and reaches the maximum rapidly. All cutting edges of the cutting tool commence machining at this point. Then, the thrust force decreases as the drill emerges from the laminate and goes to zero when the chisel edges and the cutting lips exit the material.

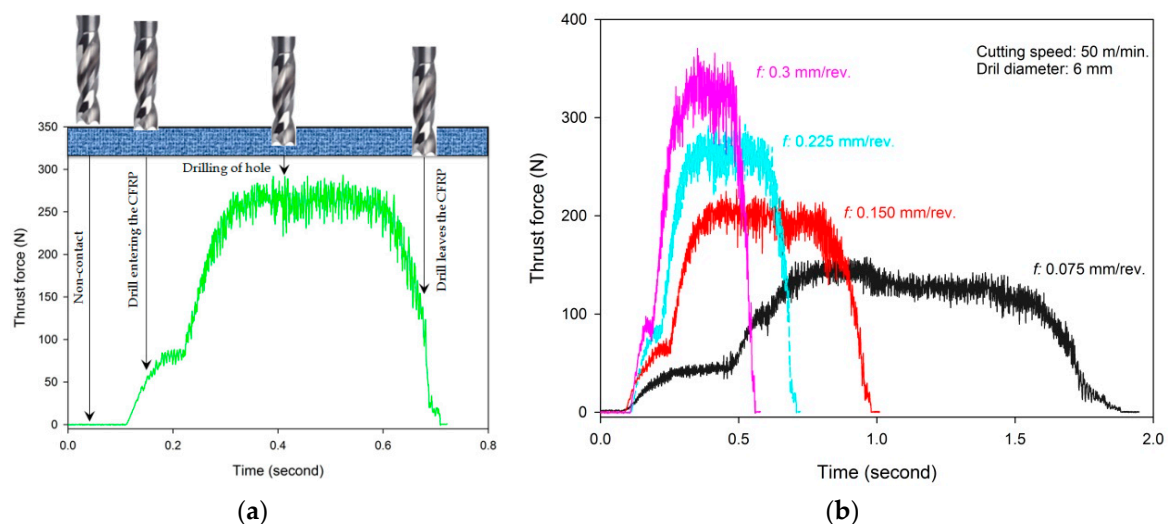


Figure 3. (a) Thrust force–time cycles for a hole; (b) Relationship between feed rate and thrust force.

The thrust forces shown in Figure 4 were obtained from the experiments by using a 50 m/min constant cutting speed, 4 and 6 mm diameter drill bits, and 0.075, 0.150, 0.225 and 0.300 mm/rev feed rates as parameters under dry and cryogenic conditions. As shown in the figure, larger thrust forces occurred under the cryogenic conditions when compared with dry conditions, and thrust force also increased depending on the increase of the feed rate and the drill diameter. An increase in the feed rate and the drill diameter increased the cross-sectional area of the unremoved chip. This led to an increased load on the tool; thus the thrust forces generated by using larger diameter drills and feed rates are greater [5,20–22]. In dry conditions, it is expected that heat formation at the cutting zone is higher during drilling since cutting fluid is not used. This heat occurrence softens the matrix (epoxy) and the thrust force decreases. In cryogenic conditions, the material is exposed to extreme cold LN_2 and the Young modulus and tensile strength of the CFRP increases as the temperature of the material decreases. Therefore, the thrust force generated in the drilling of CFRP rises in cryogenic conditions [17]. As can be seen in Figure 4, much more force was generated in drilling with a 6 mm

diameter drill bit under the cryogenic conditions. The reason for the higher thrust force when drilling in cryogenic conditions with a 6 mm diameter drill is in accordance with the explanations above.

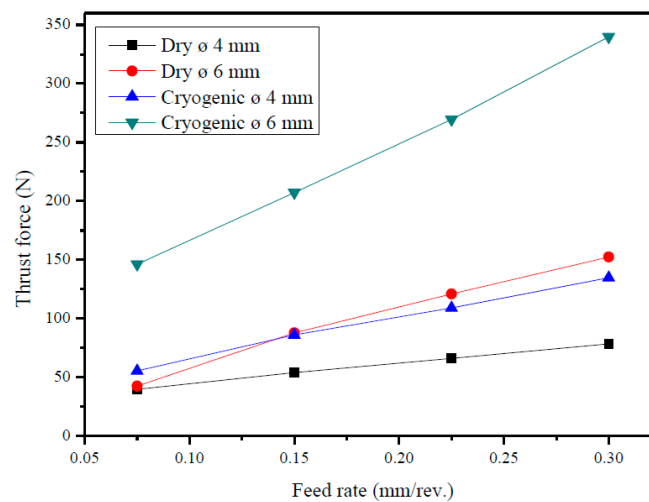


Figure 4. The effect of drill diameter, feed rate, and dry and cryogenic conditions on thrust force.

In the drilling of composites, delamination is a critical damage characterized by the separation of adjacent piles caused by an external action [23]. In a machining operation, minimizing the delamination factor is an important criterion [24]. The delamination factor was calculated by the ratio of the maximum diameter (D_{max}) of the damage zone to the nominal hole diameter (D). Figure 5 demonstrates the delamination factor variation with different feed rates. As shown in the figure, larger delamination factors occurred under cryogenic conditions when compared with dry conditions. The delamination factor increased with the increasing of the feed rate. Also, the 6 mm diameter drill generated larger delamination than the 4 mm drill. As can be seen, the difference between the delamination factors which occur under dry and cryogenic conditions increase depending on the feed rate. Also, it can be seen that there is a compliance between Figures 4 and 5. This shows that there is a strong correlation between thrust force and the delamination factor.

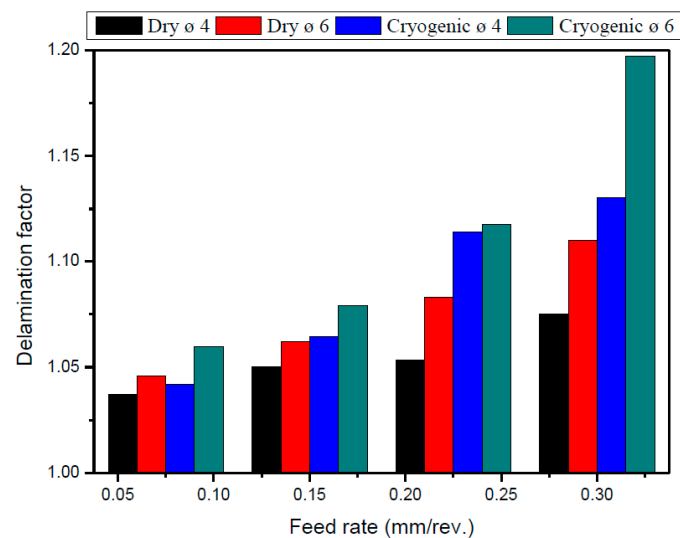


Figure 5. The effect of drill diameter, feed rate, dry and cryogenic conditions on the delamination factor.

In order to investigate the effects of the number of holes on the delamination factor and thrust force, 342 holes were drilled on a CFRP plate using 50 m/min cutting speed, 0.15 mm/rev feed rate

and 6 mm drill. Thrust force and delamination were measured for every 36 holes and Figure 6 was created from the measurements. As shown in the figure, the thrust force and delamination factor increased with increasing hole numbers. In addition, larger thrust forces and delamination factors occurred under cryogenic conditions when compared to dry conditions.

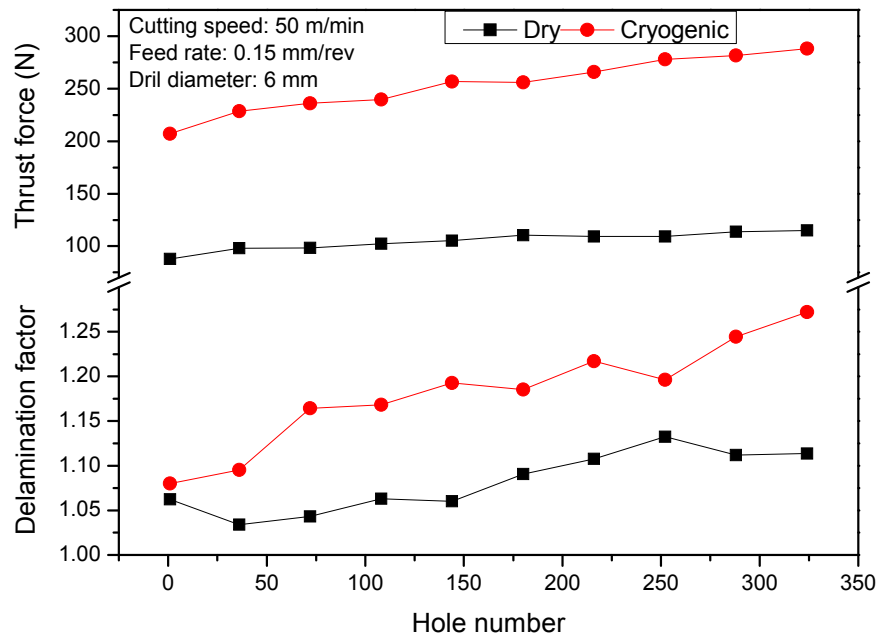


Figure 6. The effect of hole numbers on the delamination factor and thrust force.

3.2. Observation from the SEM and AFM

Holes drilled using 50 m/min cutting speed, four different feed rates (0.075, 0.15, 0.225, 0.3 mm/rev) and a 4 mm drill under both dry and cryogenic conditions divided into two parts using a hand saw, and boreholes, were examined in detail with an atomic force microscope (AFM) and scanning electron microscope (SEM). In the AFM measurements, an area with the dimensions $30 \times 30 \mu\text{m}$ was scanned with $60 \mu/\text{s}$ scanning speed. The average surface roughness (R_a) and root mean square roughness (R_q) values obtained from the AFM are shown in Figure 7 and three-dimensional (3D) views are shown in Figure 8. Three measurements were taken from the borehole surface and their average was calculated for each hole. As clearly seen in Figures 7 and 8, as the feed rate increased, surface quality deteriorated. In addition, cryogenic conditions presented better surface quality than dry conditions in the drilling of CFRP. This case can be clarified in that the liquid nitrogen supplied both cooling and lubrication and thus temperature rise was prevented in the cutting zone. The main reason why higher forces occur in cryogenic machining is explained in the literature as follows: engineering materials show much more resistance to deformation at low temperatures than at high temperatures. Also, it was reported that the Young modulus and tensile strength of CFRP increase as the temperature of the material decreases. These variations in the material properties cause much higher thrust forces to be generated during machining. Although cryogenic machining increases thrust force, it enhances surface quality. Reducing temperature at the cutting zone prevents the occurrence of thermal damage on the borehole surface and alters the material properties from ductile to brittle, thus smoother surfaces can be obtained through cryogenic machining. Besides, it has been reported that cryogenic cooling generates higher quality holes by helping to prevent tool wear [17,25,26]. The results show that cryogenic machining both decrease cutting temperatures and increase thrust forces. When the overall process is evaluated, it is concluded that cutting temperature is a more effective factor on borehole surface quality than thrust force. In addition, a combination of lower cutting temperatures, lower thrust forces and lower feed rates presented better performance.

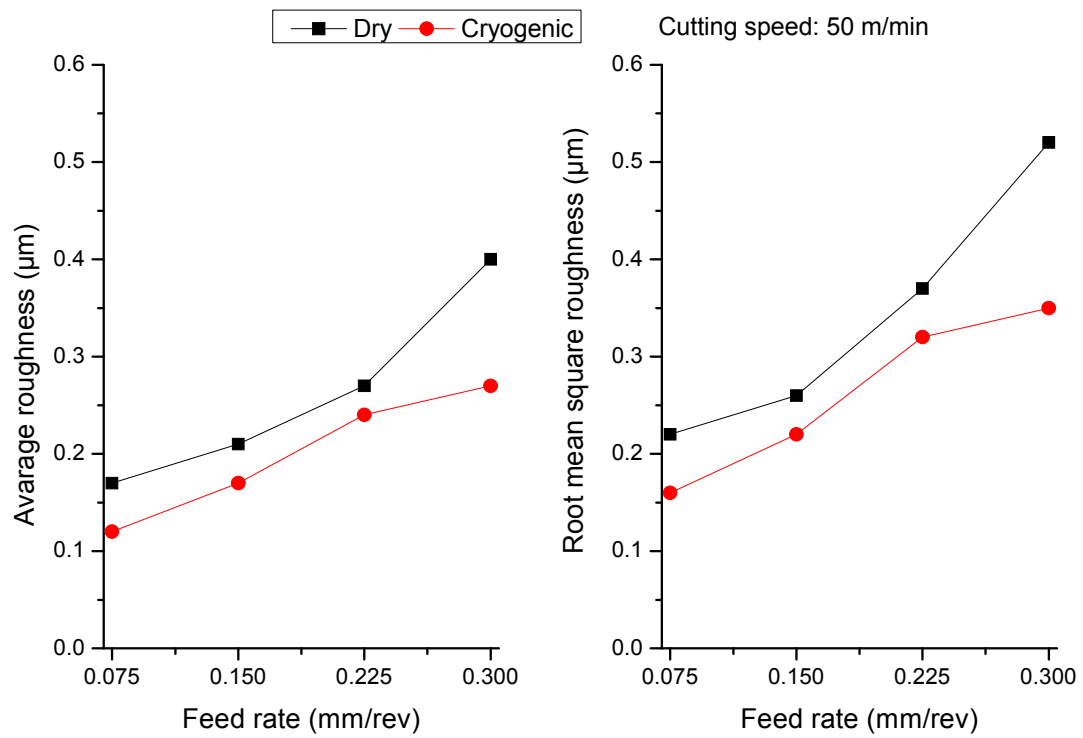


Figure 7. The average surface roughness and root mean square roughness under several machining conditions.

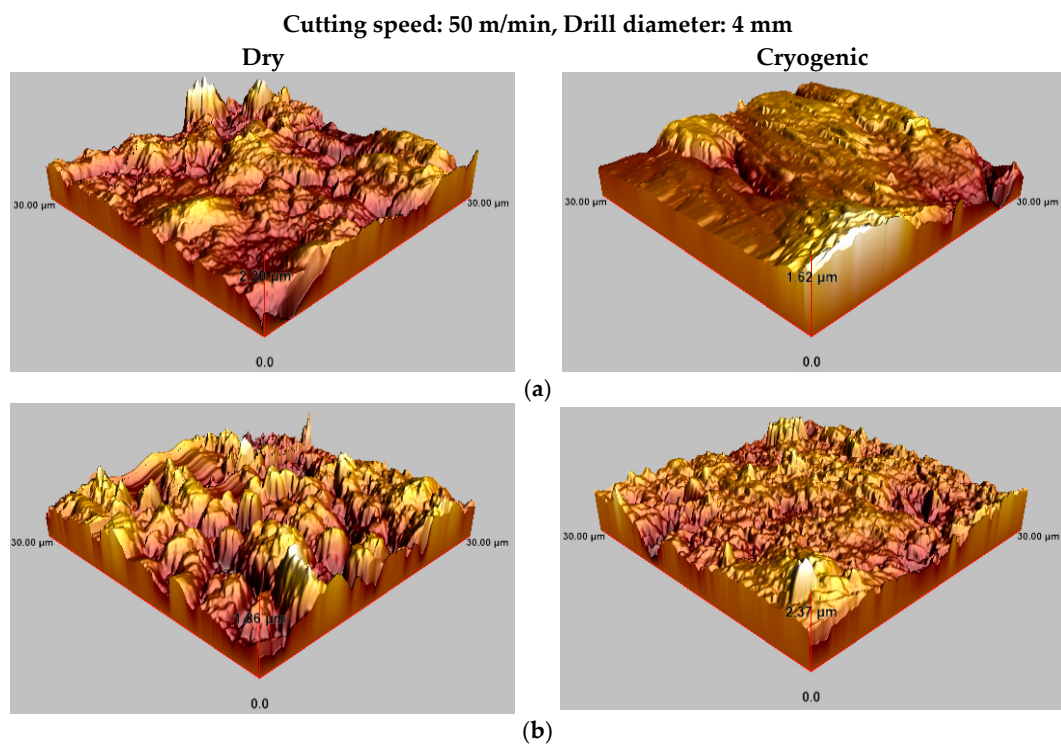


Figure 8. Cont.

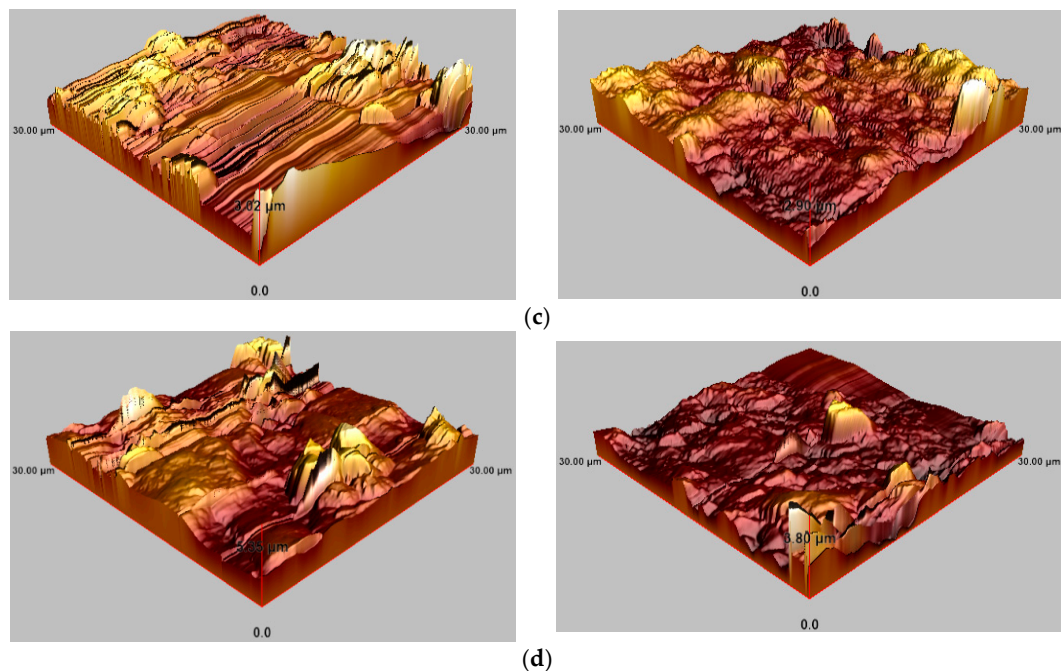


Figure 8. Three-dimensional atomic force microscope (AFM) images of the drilled holes at different feed rates. (a) Feed rate: 0.075 mm/rev; (b), Feed rate: 0.150 mm/rev; (c) Feed rate: 0.225 mm/rev; (d) Feed rate: 0.3 mm/rev.

Drilling in dry conditions generates higher temperatures and thus lower forces occur, but drilling with LN_2 reduces cutting zone temperature excessively, so higher forces occur. Low thrust forces and low cutting temperatures are desired so as to obtain better machining quality. Higher temperatures and larger cutting forces bring about undesirable defects such as delamination, fiber pull out and rough surface finish in the drilling of heterogeneous materials. The surface morphology of the drilled hole surface was studied using SEM imaging to identify the type of drilling-induced damage and defects. In this SEM study, fiber pullout, fiber breakout, matrix crack and matrix smearing were the primary surface defects or damages observed. A total of 324 holes were drilled on a CFRP material using a constant 50 m/min cutting speed and 0.15 mm/rev feed rate in dry and cryogenic conditions. The SEM images of the boreholes are demonstrated in Figure 9 for dry conditions and Figure 10 for cryogenic conditions. In Figure 9, it is shown that some partitions of carbon fibers were pulled away from the machined surface leaving cavities that caused a rough surface when dry drilling.

In dry drilling, high cutting temperatures lead to the softening and decomposing of the matrix, resulting in poor support for fibers. This causes fibers to be pulled out and removed. Consequently, high surface roughness occurs due to cavities. Figure 10 shows that a smoother surface is obtained when using LN_2 . Lower temperatures increase the durability of the matrix and help to maintain the position of fibers and thus lower surface roughness can be obtained in the cryogenic drilling of CFRP. According to the SEM images, more damage occurred in the 324th hole and damage is marked with a red circle. Fewer defects (pull out and cavities) were observed in the 324th hole drilled using LN_2 than that drilled in dry conditions. As a consequence, usage of LN_2 provides a benefit to surface finish by reducing the machining temperature.

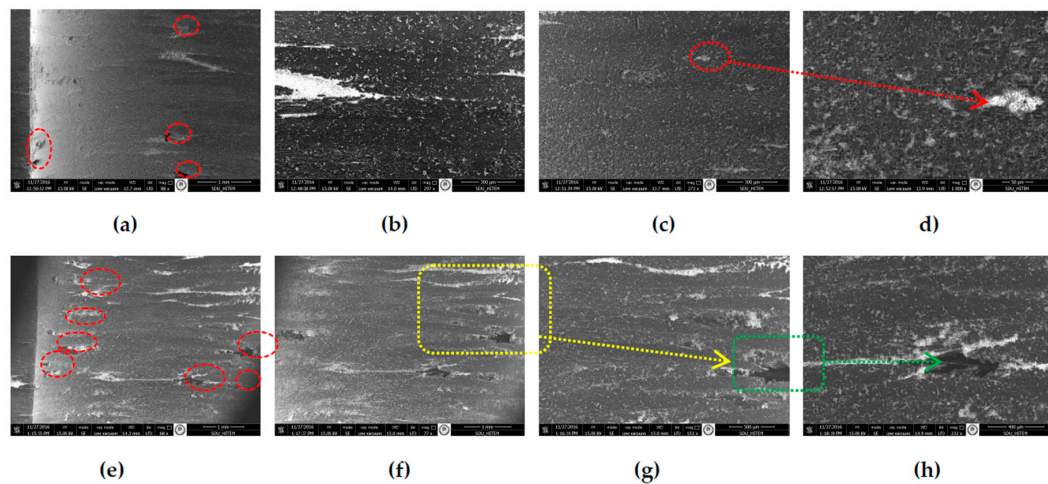


Figure 9. SEM images of drilled holes performed under dry conditions for the 1st (a–d) and 324th (e–f) holes.

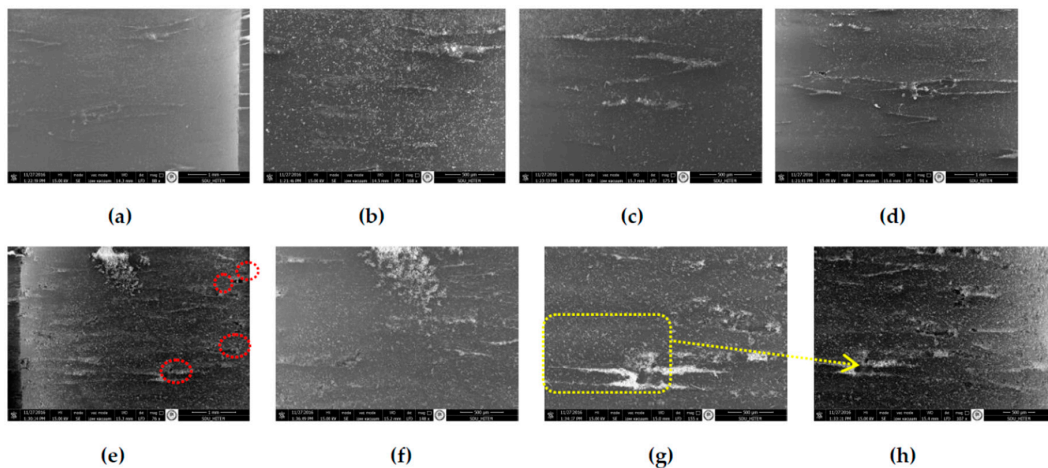


Figure 10. SEM images of drilled holes performed under cryogenic condition for the 1st (a–d) and 324th (e–f) holes.

3.3. Tool Wear

Due to rapid tool wear and catastrophic tool failure, various problems such as short tool life, poor hole quality, low cutting efficiency, and high machining cost may occur. The formation of tool wear gives rise to several undesirable results, e.g., large machining force generation, heat accumulation in the cutting zone, extreme power consumption, etc. [27]. A study of the wear of the cutting tools was made using a SEM. Figure 11 shows the drill wear for a constant cutting speed (50 m/min) and feed rate (0.15 mm/rev) after drilling 324 holes in CFRP under dry and cryogenic conditions. Corner wear was observed in drilling experiments performed under both dry and cryogenic conditions. When a new drill is examined carefully, one can see that the tool's corner is highly sharp. From the figure, it can be seen that the dominant wear is at the outer corner and on the main cutting edge during the dry drilling of CFRP. These results point out the severe abrasive wear of the drill's carbon fibers [28]. Wearing of the chisel edge was predominantly seen in the tests using cryogenic cooling. This can also be an indication of the high forces induced during the cutting process [29]. This is basically owing to the very high stress in the flow zone of the tool–workpiece interface that brings about erosion wear of the chisel edges [30].

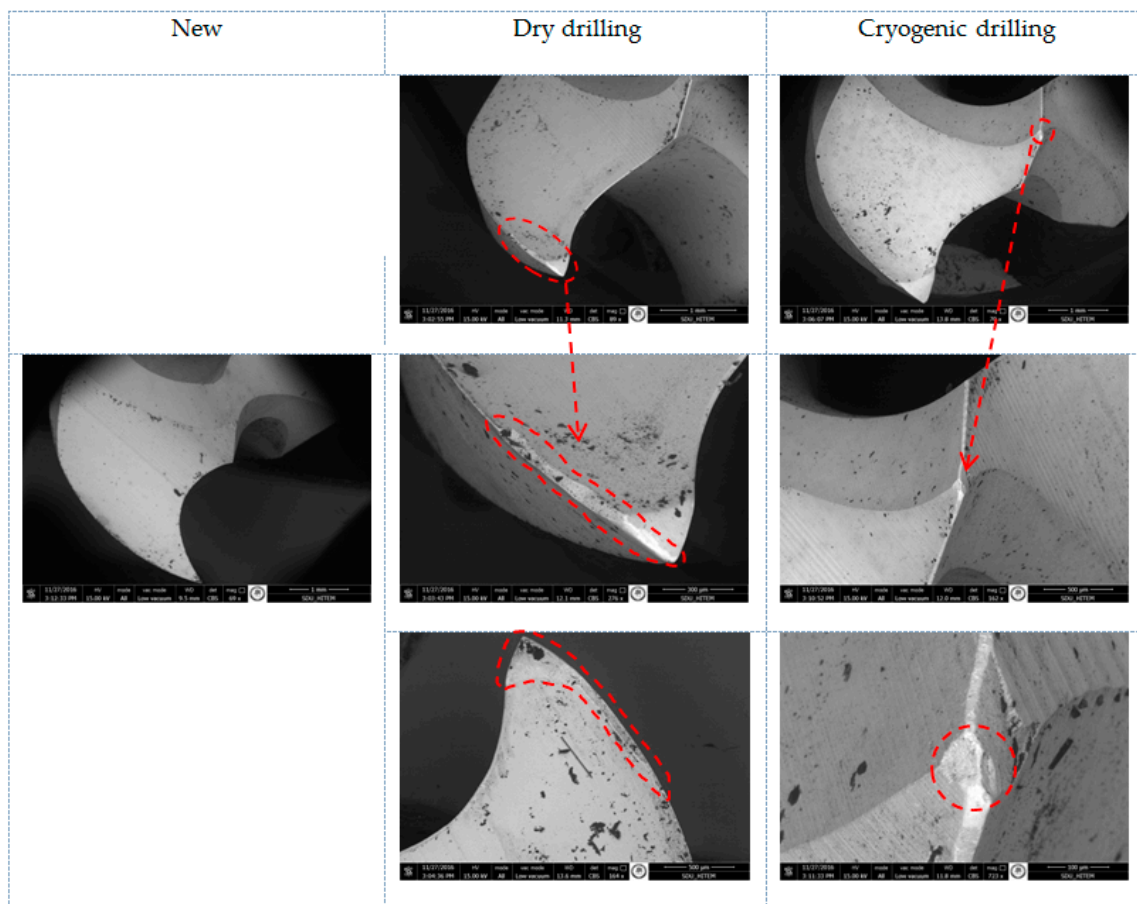


Figure 11. Drill wear for the dry and cryogenic condition tests after 324 holes drilled.

4. Results

Drilling performance of CFRP material was experimentally investigated using constant cutting speed, different feed rates and drill bits (4 and 6 mm diameter) under dry and cryogenic conditions. The results of the comprehensive experimental study are given below.

- When CFRP is exposed to excessive cold under cryogenic conditions, the temperature of the material decreases extremely. This decrease in the temperature leads to an increase in Young modulus and tensile strength and also makes the material stiffer, more brittle, and fragile. As materials are highly resistant to deformation at low temperatures, the thrust forces generated during the drilling of CFRP in cryogenic conditions are larger when compared with dry conditions.
- The high temperatures that occurred in the dry drilling of CFRP may cause several problems if temperatures in the cutting zone surpass the glass transition temperature of the matrix. As using a cryogenic coolant prevents temperature increase in the cutting zone and provides lubrication, less damaged, smoother, and higher quality surfaces were obtained under cryogenic conditions.
- Owing to the fact that the temperature increase in the cutting zone is small under cryogenic conditions, there is less tool wear compared to dry conditions.
- According to the results of this study, 4 mm diameter drills performed better than 6 mm diameter drills in all tested cases. Smaller diameter drill bits should thus be chosen unless there is a restriction in terms of design.
- Using cryogenic coolant is profitable when drilling CFRP since it enhances machining efficiency by reducing heat occurrence in the cutting zone during machining, rapidly transferring heat from the cutting zone and allowing high-speed machining.

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Author Contributions: Gultekin Basmaci and A. Said Yoruk designed the experiments and measured the AFM and SEM; Ugur Koklu, Sezer Morkavuk and Gultekin Basmaci performed the experiments, analysed the data and wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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